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Our long-term technical goal is to produce a tested tangent linear model (TLM) and adjoint model (ADM) for ROMS/TOMS (Regional Ocean Modeling System/Terrain-Following Ocean Modeling System) that is suitable for general use by the ROMS/TOMS community and to develop computational platforms based on the TLM and ADM for 4D variational data assimilation (4DVar), ensemble forecasting and sensitivity analysis. Our long-term scientific goal is to model and predict the mesoscale circulation and the ecosystem response to physical forcing in the various regions of the world ocean through state estimation.

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ROMS/TOMS Tangent Linear and Adjoint Models: Testing and Applications

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LONG-TERM GOALS

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OBJECTIVES

We seek to develop and test data assimilation algorithms that use the adjoint model for ROMS/TOMS, which is a state-of-the-art ocean model for high-resolution scientific and operational applications (Haidvogel et al., 2000; Shchepetkin and McWilliams, 2003). These will be used for fitting ROMS simulations to observations via data assimilation techniques, such as 4DVar and the representer method (Chua and Bennett, 2001). The resulting codes will be suitable for exploring the predictability of the circulation in regional ocean models in a variety of dynamical regimes.

APPROACH

This is fundamentally a collaborative effort involving the University of Colorado (A. Moore), Rutgers University (H. Arango) and Scripps (B. Cornuelle, A. Miller, D. Neilson and former student and post-doctoral scholar E. Di Lorenzo, who is now Assistant Professor at Georgia Tech). Our approach has been to write the tangent linear and adjoint models for ROMS/TOMS by hand. As the development has been accomplished, the assimilation scheme has been preliminarily tested in various scenarios involving observations, especially using 4DVar. The Scripps contingent is testing the 4DVAR scheme for ROMS/TOMS in the California Current CalCOFI region in physical-biological data syntheses and model forecast scenarios.

WORK COMPLETED

The ROMS/TOMS adjoint team met many times over the past four years in intensive tangent linear model, adjoint model and platform development writing and testing sessions. A working 2D and 3D tangent linear and adjoint model is now running and being used in various idealized and realistic applications.

The computational platforms for computing eigenmodes, adjoint eigenmodes, singular vectors, forcing singular vectors, stochastic optimals, and pseudospectra of the tangent linear propagator have been completed and tested. The observational infrastructure, cost function, pre-conditioning and descent algorithms for 4DVar have been built and are being tested. We are using several 4DVar data assimilation schemes that have been developed for ROMS/TOMS. For cases in which the dynamics are imposed as a strong constraint (i.e. no model error assumed) we use an incremental 4DVar approach similar to that used operationally at some numerical weather prediction centers. In the case where errors are admitted in the model we use the newly developed Oregon State University Inverse Ocean Model (IOM) system (Chua and Bennett, 2001). The IOM requires an additional version of the model that computes a linear estimate of the total state of the system as opposed to perturbations about some existing solution of the non-linear ROMS. This second linearized form of ROMS (denoted here as LM) has been developed under a separate NSF funded effort. This component of the project involves significant collaboration with Dr. Boon Chua at OSU.

Currently, we are developing a computational platform for ensemble prediction based on the TLM and ADM of ROMS/TOMS. The plan is to use Singular Vectors (SVs) to perturb the initial conditions of each ensemble member. Perturbing the system along the most unstable directions of the state space defined by the SVs yields information not only about the first moment (ensemble mean) of the Probability Density Function (PDF) but also about the tails of the PDF, specifically its second moment (the ensemble spread).

Some of the results are described by Moore et al. (2003) and Arango et al. (2003), including the tangent linear and adjoint components of ROMS, and examples of singular vectors and stochastic optimals for a time-evolving double gyre ocean model.

RESULTS

ROMS is now configured with a wide array of open boundary conditions ranging from simple "clamped" conditions and "sponge-layers" to more complicated radiation boundary conditions. Our experience has been that the presence of open boundary conditions represents a considerable technical challenge for 4DVar applications using ROMS. Radiation conditions are particularly challenging since the TL and AD versions of these introduce additional mathematical and input/output management complications. The TL and AD versions of all available open boundary condition options for ROMS have been coded and tested, but further work is needed to understand their behavior in the wide range of current ROMS applications.

An extensive set of identical twin data assimilation has revealed that the convergence of the ROMS 4DVar assimilation algorithm is very sensitive to the preconditioning that is used for the cost function gradient and minimization algorithm, and the relative weight in the cost function that is given to surface and deep ocean temperatures. Our experience with the identical twin experiments will be a valuable guide for the real data applications that we are now planning in the other regions.

Preliminary generalized stability theory calculations in the Southern California Bight region have revealed that the circulation may be very sensitive to uncertainties at or near the model open boundaries. These errors appear to propagate through the model domain as coastally trapped waves. To illustrate, Figs. 1a,b show a snapshot of the ROMS Southern California Bight surface circulation on a particular day. The model horizontal resolution in this case is 10 km and a

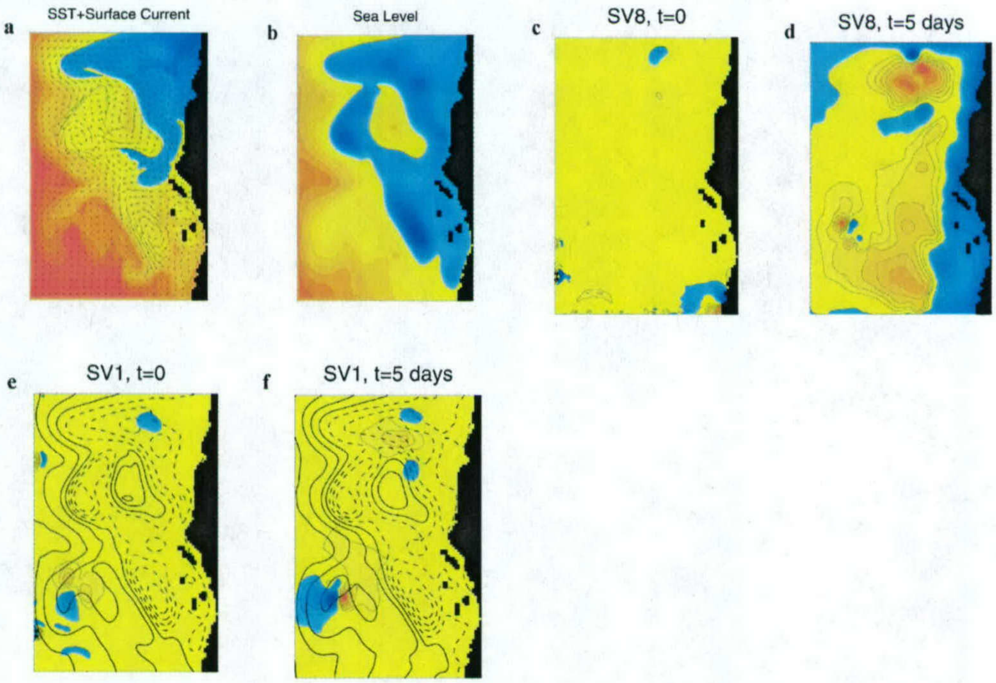

Figure 1. □,b) Sn□pshots of SST, surf□ce current □nd se□level elev□tion. c-f) Two ex□mple singul□r vectors. The initi□l se□level elev□tion is shown in c □nd e, □nd the s□me field 5 d□ys l□ter is shown in d □nd f. The solid contours in e □nd f □re b□sic st□te se□level elev□tion from b. In c-f the contour interv□l is □rbitr□ry, □nd w□rm (cold) colors indic□te positive (neg□tive) elev□tion perturb□tions.

combination of radiation conditions and sponge layers are used at the non-coastal boundaries. Figures 1c,d show the initial and final sea surface elevation of a rapidly growing singular vector that was computed over a 5day interval on a time-evolving circulation starting from Figs. 1a,b. The perturbation energy of the ocean state was used as a measure of singular vector growth, and over the 5 day period this increases by a factor ~200. Notice how perturbations near the southern open boundary can quickly grow to influence other parts of the model domain.

Other members of the singular vectors spectrum identify others areas of sensitivity that are primarily associated with confluent and diffluent regions of the California Current System (CCS). An example is shown in Figs. 1e,f that show the initial and final sea surface elevation of a different singular vector. Notice how in this case the perturbations initially favor regions that are just upstream of areas where the CCS circulation is converging or diverging (Fig. 1e) as evidenced by contours of the basic state sea level elevation (also shown in Figs, 1e,f) which are a good surrogate for surface streamlines. As the perturbations evolve they are advected downstream into regions of shear flow that represent significant sources of potential and kinetic energy which allow them to grow.

IMPACT/APPLICATIONS

The tangent linear and adjoint model for ROMS/TOMS will provide a powerful tool for exploring data assimilation issues, such as: sensitivity to initial conditions, uncertainties in surface forcing, predictability, and ocean dynamics.

TRANSITIONS

The work completed here will be part of the ROMS/TOMS utilities that will be freely available to all interested users.

RELATED PROJECTS

The work described here is in collaboration with Dr. Hernan Arango of Rutgers University and Dr. Andrew Moore of the University of Colorado. These investigators are supported by the following grants: "ROMS/TOMS Tangent Linear and Adjoint Models: Testing and Applications", PI Hernan Arango, grant number N00014-00-1-0227; "Application of the ROMS/TOMS Tangent Linear and Adjoint Models to the Littoral Ocean and Semi-Enclosed Seas", PI Andrew M. Moore, grant number N00014-01-1-0209.

Moore, Arango, Miller and Cornuelle have a project funded by NSF (lead PI: A. Bennett, OSU) entitled "Modular Ocean Data Assimilation". The goal is to use the infrastructure of the Inverse Ocean Modeling (IOM) system of Chua and Bennett (2001) in conjunction with the ROMS/TOMS tangent linear and adjoint models for ocean data assimilation.

REFERENCES

Arango, H.G., A.M. Moore, A.J. Miller, B.D. Cornuelle, E. Di Lorenzo and D.J. Neilson, 2003: The ROMS Tangent Linear and Adjoint Models: A comprehensive ocean prediction and analysis system, *IMCS Rutgers Tech. Report.*

Chua, B.S., and A.F. Bennett, 2001: An inverse ocean modeling system. *Ocean Modelling*, **3**, 137-165.

Haidvogel, D.B., H.G. Arango, K. Hedstrom, A. Beckmann, P. Malanotte-Rizzoli, and A.F. Shchepetkin, 2000: Model evaluation experiments in the North Atlantic Basin: Simulations in nonlinear terrain-following coordinates, In: *Ocean Circulation Model Evaluation Experiments for the*

North Atlantic Basin, E. P. Chassignet and P. Malanotte-Rizzoli (Eds.), *Dyn. Atmos. Oceans*, **32**, Elsevier Sci. Ltd., 239-281.

Moore, A. M., H. G Arango, E. Di Lorenzo, B. D. Cornuelle, A. J. Miller and D. J. Neilson, 2003: A comprehensive ocean prediction and analysis system based on the tangent linear and adjoint of a regional ocean model. *Ocean Modelling,* **7**, 227-258.

Shchepetkin, A. F. and J. C. McWilliams, 2003: The regional ocean modeling system: A split-explicit, free surface, topography-following coordinate ocean model, *J. Comp. Phys*., submitted.

PUBLICATIONS

Arango, H.G., A.M. Moore, A.J. Miller, B.D. Cornuelle, E. Di Lorenzo and D.J. Neilson, 2003: The ROMS Tangent Linear and Adjoint Models: A comprehensive ocean prediction and analysis system, *IMCS Rutgers Tech. Report***.**

Di Lorenzo, E., 2002: Seasonal dynamics of the surface circulation in the Southern California Current System. *Deep-Sea Research,* **50**, 2371-2388. .

Di Lorenzo, E., A. J. Miller, D. J. Neilson, B.D. Cornuelle, and J. R. Moisan, 2003: Modeling observed California Current mesoscale eddies and the ecosystem response. *International Journal of Remote Sensing*, **25**, 1307-1312.

Miller, A. J., E. Di Lorenzo, D. J. Neilson, B. D. Cornuelle, and J. R. Moisan, 2000: Modeling CalCOFI observations during El Nino: Fitting physics and biology. *California Cooperative Oceanic Fisheries Investigations Reports*, **41**, 87-97.

Moisan, J. R., A. J. Miller, E. Di Lorenzo and J. Wilkin, 2004: Modeling and data assimilation. In: *Remote Sensing in Coastal Aquatic Environments*, Chapter 13, *sub judice.*

Moore, A. M., H. G Arango, E. Di Lorenzo, B. D. Cornuelle, A. J. Miller and D. J. Neilson, 2003: A comprehensive ocean prediction and analysis system based on the tangent linear and adjoint of a regional ocean model. *Ocean Modelling,* **7**, 227-258.